

# Optimization-Based Feedforward Control for a Drop-on-Demand Inkjet Printhead

Amol A. Khalate, Xavier Bombois, Robert Babuška, Herman Wijshoff and René Waarsing

**Abstract**—The printing quality delivered by a Drop-on-Demand (DoD) inkjet printhead is limited due to operational issues such as residual oscillations in the ink channel and the cross-talk between the ink channels. The maximal jetting frequency of a DoD inkjet printhead can be increased by quickly damping the residual oscillations and by bringing in this way the ink channel to rest after jetting the ink drop. This paper proposes an optimization-based method to design the input actuation waveform for the piezo actuator in order to improve the damping of the residual oscillations. The narrow-gap model is used to predict the response of the ink channel under the application of the piezo input. Simulation and experimental results are presented to show the applicability of the proposed method.

## I. INTRODUCTION

The ability of Inkjet technology to deposit materials with diverse chemical and physical properties on substrate has made it an important technology for both industry and home use. Apart from conventional document printing, the inkjet technology has been successfully applied in the areas of electronics, mechanical engineering, life sciences [1]. This is mainly thanks to the low operational costs of the technology. Typically, a drop-on-demand (DoD) inkjet printhead consists of several ink channels in parallel. Each channel is provided with a piezo-actuator, which on application of a standard actuation voltage pulse can generate pressure oscillations inside the ink channel. These pressure oscillations push the ink drop out of the nozzle. A detailed description of the droplet jetting process can be found in [2]. The print quality delivered by an inkjet printhead depends on the properties of the jetted drop, i.e., the drop velocity, the jetting directionality and the drop volume. To meet the challenging performance requirements posed by new applications, these drop properties have to be tightly controlled.

The performance of the inkjet printhead is limited by two operational issues. The first issue is the *residual pressure oscillation*. The actuation pulses are designed to provide an ink drop of a specified volume and velocity under the assumption that the ink channel is in steady state. Once the ink drop is jetted the pressure oscillations inside the ink channel takes several micro-seconds to decay. If the next

ink drop is jetted before settling of these residual pressure oscillations, the resulting drop properties will be different from the previous drop. This can degrade the printhead performance. The second operational issue is the *cross-talk*. The drop properties through an ink channel are affected when its neighboring channels are actuated simultaneously. The drop velocity variation caused by the cross-talk is much less significant than the one caused by the residual oscillations and will not be addressed in this contribution.

A consequence of the residual oscillations in the ink channel is that the velocity of the drops will only be constant if these drops are jetted at a low frequency. Indeed, if we jet at a high frequency, drops will be jetted before the oscillations in the ink channel have completely disappeared and these residual oscillations will modify the drop velocity. Since a printhead may have to jet drops at different frequencies when printing a bitmap, it is required to be able to jet ink drops with a constant velocity at any rate ranging from 20kHz to 70kHz. Given this fact, an important characteristic is the so-called DoD curve which represents the ink drop velocity as a function of the jetting frequency (which is also called the DoD frequency). Ideally, the DoD curve must be flat. However, for the reasons given above, this DoD curve is far from flat in practice. Our goal in this paper is to flatten the DoD curve by designing an optimal piezo actuation pulse. Since the residual pressure oscillations in the ink channel is the main reason for which the DoD curve is not flat, our optimal actuation pulse will have as major objectives to reduce the residual oscillations.

Generally, the piezo actuation consists of only one positive trapezoidal pulse which gives good result when only one drop is jetted and we will call this particular actuation pulse the standard pulse. The parameters of the standard pulse are generally obtained by exhaustive studies on a complex numerical model of the inkjet printhead or on an experimental setup [3], [4]. Wave propagation analysis is used in [5] to design a piezo actuation pulse in order to suppress the residual oscillations. The piezo actuation waveform consists of two positive trapezoidal pulses. The optimal starting point for the second pulse is proposed to be 1.5 times the fundamental period of the measured residual pressure oscillations. We will see later that with the proposed feedforward control it is possible to jet ink drops even faster than with the method in [5]. Unlike the previous approaches we will tackle the operational issues of the DoD inkjet printhead with a system and control approach.

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For this purpose, we require a model of the system that we want to control. Here, we will consider a model  $H(z)$  relating the piezo input voltage (i.e., the input) to the velocity of the so-called meniscus (i.e., the output) [6], [2]. The meniscus is the ink and air interface in the nozzle. We consider this particular model since it is well known that the velocity of the meniscus is a good measure of the pressure in the ink channel. Consequently, reducing the residual oscillations of the meniscus velocity is equivalent to reducing the residual pressure oscillations in the ink channel.

Using this model, we will be able to compute the optimal piezo actuation. Mainly due to the limitations of the driving electronics (see Section II.A.), the optimal input cannot be computed using a feedback controller, but must be computed off-line based on the model  $H(z)$  (feedforward control).

In the literature, we can find other applications of system/control theory to design off-line the optimal piezo actuation. In [7], the authors propose to inverse  $H(z)$  to design the actuation pulse. As the system  $H(z)$  is strictly proper and non-minimum phase, it cannot be inverted directly and approximations have to be used. In [2], an iterative learning approach is used to design the optimal pulse off-line. The main drawback of the approach in [2] (but also of the one in [7]) is that it is not possible to put a-priori constraints on the shape of the optimal pulse while such constraints are generally present in practice. Indeed, the driving electronics are generally only able to generate trapezoidal shapes for the piezo actuation input. The approach presented in this paper allows us to deal with such shape constraints. We propose to parameterize the class of piezo input satisfying these shape constraints and to determine the optimal input within this class using an optimization-based approach.

For this purpose, we will suppose that the possible inputs can be parameterized as  $u(t, \theta)$  with  $\theta$  a parameter vector. We then design a template  $y_{ref}(t)$  for the desired meniscus velocity, i.e., a the meniscus velocity profile with fast decaying residual oscillations. Based on this template  $y_{ref}(t)$  and the transfer function  $H(z)$  an optimal actuation pulse  $u(t, \theta_{opt})$  will be determined as the one minimizing the norm of the tracking error. The proposed method is similar to model predictive control (MPC) [8]. Both the approaches try to reduce the tracking error using an optimization algorithm. The methods differ in the computation of the control input. In the standard MPC algorithm no constraint on the shape of the control input is imposed.

## II. SYSTEM DESCRIPTION AND MODELING

The DoD inkjet printhead under investigation is made up of two arrays of 128 ink channels each. A cross-sectional view of an inkjet channel is shown in Fig.1. The ink channel is carved in the channel plate. A filter is placed on top of the ink channel to remove impurities from the liquid ink. A metallic nozzle-plate with drilled holes, which act as a nozzle, is attached at the bottom of the channel plate. One wall of the ink channel is formed by a flexible foil to which a piezo unit is attached. The piezo unit acts as

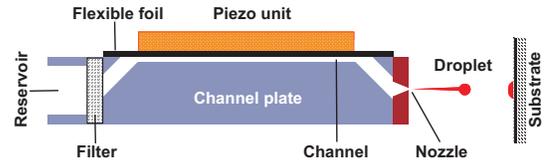


Fig. 1. A cross-sectional view of an inkjet channel.

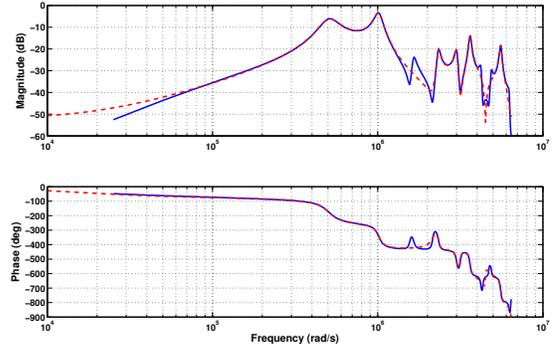


Fig. 2. Frequency response of the narrow-gap model  $\mathcal{H}(j\omega)$  (blue-solid) and the approximated transfer function  $H(z)$  (red-dashed).

an actuator and on application of a voltage, it deforms the wall (flexible foil) of the ink channel. The deformation of the ink channel generates pressure waves inside the ink channel. When specific conditions are met, a droplet is jetted [2]. Several analytic and numerical models are available for the inkjet channel dynamics in the literature. For control applications, one prefers a simpler model with sufficient accuracy. Therefore, we selected the ‘narrow-gap model’ [9] for control synthesis purpose. It describes the dynamic system from the piezo input voltage  $u$  to the meniscus velocity  $y$ . The detailed derivation of the model for the considered DoD inkjet printhead using the narrow channel theory [9] is given in [6]. In this model, a narrow channel wave equation is used to describe the acoustics inside the ink channel. This wave equation is a simplified form of the Navier-Stokes equation (conservation law for fluids) [6].

In the narrow-gap model, the frequency response of  $\mathcal{H}(j\omega)$  is computed using the sine sweep method. This method consists of solving the wave equation for a sinusoidal input signal  $|u|e^{j\omega_1 t}$  at a certain frequency  $\omega_1$ . Supposing that the corresponding meniscus velocity is given by  $y(\omega_1)$ , the frequency response of the system at  $\omega_1$  is given by:

$$\mathcal{H}(j\omega) \Big|_{\omega=\omega_1} = \frac{y(\omega_1)}{|u|e^{j\omega_1 t}} \quad (1)$$

By repeating this procedure over a fine frequency grid, we obtain the frequency response given in Figure 2. It can be seen that the system is non-minimum phase. This empirical frequency function can not be used for the optimization leading to the optimal piezo actuation. Hence, we fit a low order discrete-time model  $H(z)$  to the frequency response obtained from the narrow-gap model. The non-minimum

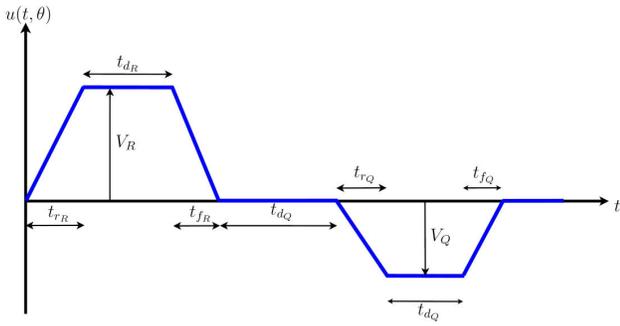


Fig. 3. Proposed piezo actuation pulse.

phase behavior present in the frequency response is also captured by the fitted model  $H(z)$  shown by the dashed line in Fig. 2. This approximated discrete time model will be used for further analysis.

### III. FEEDFORWARD CONTROL DESIGN

In this section, we will first present the control objectives and foreseen limitations. The proposed optimization based feedforward control is discussed subsequently.

#### A. Limitations of the control system

The printhead under investigation has very limited control capabilities. The possibility to use feedback control is ruled out due to the following limitations of the actuation system

- No sensor is provided for real-time measurement of the channel pressure or the meniscus velocity.
- The driving electronics limit the range of the actuation pulses that can be generated in practice. The only possible choice of the actuation pulse is the trapezoidal waveform.
- The sample time required for control computation must be very short due to high drop jetting (DoD) frequency.

In this scenario, the ink channel dynamics can be controlled using a feedforward strategy. The goal is to generate a trapezoidal actuation pulse for the piezo actuator such that the control objectives are met. We know that the standard pulse can jet a single ink drop of the specified properties. But it is not capable of damping the residual oscillations generated after jetting the ink drop. Therefore, we have proposed to add a negative trapezoidal pulse in addition to the standard positive trapezoidal pulse to damp the residual oscillations, see Fig. 3. The optimal starting time for this additional negative pulse is approximately equal to the fundamental period of the channel pressure signal. This enables the proposed actuation pulse to jet ink drop faster compared to [5]. It consists of a positive trapezoidal pulse called as a resonating pulse, which is responsible for jetting the ink drop. The negative trapezoidal pulse which damps the residual oscillations is called the quenching pulse. The actuation pulse can be characterized by the rise time ( $t_r$ ), the dwell time ( $t_w$ ), the fall time ( $t_f$ ) and the amplitude ( $V$ ) of both the resonating and the quenching pulse. The time interval

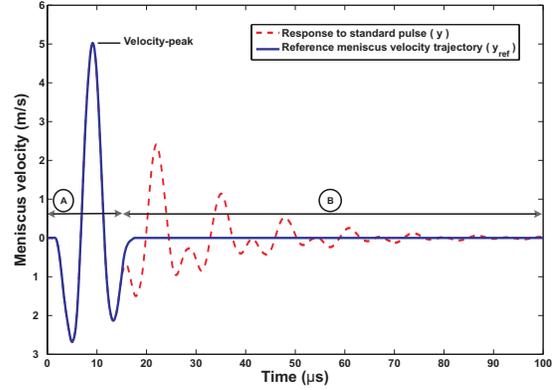


Fig. 4. Reference meniscus velocity trajectory.

between the resonating and the quenching pulses is  $t_{dQ}$ . Thus, an actuation pulse  $u(t, \theta)$  is defined by the parameter vector  $\theta = [t_{rR} \ t_{wR} \ t_{fR} \ V_R \ t_{dQ} \ t_{rQ} \ t_{wQ} \ t_{fQ} \ V_Q]^T$ . The optimal parameter vector will be determined using the approach that will be presented in the sequel.

#### B. Control Objective

In order to define the optimization problem leading to the optimal parameter vector  $\theta_{opt}$ , we need to define a template  $y_{ref}(t)$  for the desired meniscus velocity. Recall that the standard pulse allows to jet one drop at the desired velocity, but that the residual oscillation generated by this standard pulse perturbs the subsequent drops. Such a behavior can be observed in Fig. 4 (dashed line) where we represent the response of the model  $H(z)$  to the standard pulse. The meniscus velocity (which is an image of the pressure in the ink channel) presents a response in two parts. Part A is the response which allows the drop to be jetted at the right velocity. The major feature of Part A is in fact the so-called velocity peak (equal to five). Part B is the residual oscillation. Consequently, the desired meniscus velocity  $y_{ref}(t)$  will be equal to the one with the standard pulse in part A and will be zero in Part B. This template  $y_{ref}(t)$  is represented in solid line in Figure 4. If the actuation pulse is designed in such a way that the meniscus velocity  $y(t)$  follows the reference trajectory  $y_{ref}(t)$ , then the channel will come to rest very quickly after jetting the ink drop. This will create the condition to jet the ink drops at higher jetting frequencies.

#### C. Optimization based feedforward control

We are now ready to formulate the optimization problem which will lead to the optimal piezo input. The optimal input is the trapezoidal input  $u(t, \theta)$  which minimizes the difference between the reference trajectory  $y_{ref}(t)$  and the meniscus velocity  $y(t) = H(z)u(t, \theta)$  subject to the constraints on the shape of the actuation pulse. More precisely, we can define the objective function as the following sum of weighted square errors

$$\mathcal{J}(\theta) = \sum_{t=0}^T w(t)(y_{ref}(t) - H(z)u(t, \theta))^2, \quad (2)$$

where  $T$  is chosen  $100\mu s$ ,  $w(t)$  is an user-defined time-domain weighting,  $H(z)$  is the discrete-time model from piezo input to the meniscus velocity and  $u(t, \theta)$  is the proposed actuation pulse parameterized by the parameter vector  $\theta$  (see section III.A).

The optimal actuation pulse parameter  $\theta_{opt}$  can be obtained by minimizing the objective function  $\mathcal{J}$ . Thus the optimization problem is

$$\theta_{opt} = \arg \min_{\theta} \mathcal{J}(\theta), \quad (3)$$

subject to

$$\theta_{LB} \leq \theta \leq \theta_{UB}, \quad (4)$$

where,  $\theta_{LB}$  and  $\theta_{UB}$  are the vectors containing the lower and the upper bounds on each element of the parameter vector  $\theta$ .

This is a constrained nonlinear optimization problem and can be solved off-line using standard algorithms.

**Remark:** Such as in [7], the objective function (2) allows to perform an inversion of the dynamics. However, the method proposed above allows to perform this inversion without any approximations.

#### IV. SIMULATION RESULTS

In the previous section, our control objectives and the related problem for feedforward control design have been presented. The nonlinear optimization problem (3)-(4) is solved by using the command `fmincon` from the optimization toolbox of MATLAB. The weighting  $w(t)$  is designed to penalize the error more in the second part of the reference trajectory. The optimal parameter vector obtained after solving the optimization problem (3)-(4) is given as follows

$$\theta_{opt} = [2.0 \ 2.5 \ 1.3 \ 22.5 \ 7.6 \ 1.3 \ 0.4 \ 4.4 \ -13.2]^T$$

Note that in the parameter vector  $\theta$ , the time parameters ( $t_r, t_w, t_f, t_{dQ}$ ) of the actuation pulse are expressed in  $\mu s$ .

We compare the standard pulse and the optimal actuation pulse in the Fig.5. As expected, the optimal piezo actuation pulse contains two components, the resonating pulse and the quenching pulse. The quenching pulse deflect the piezo actuator in order to damp the residual oscillations. This enables the meniscus velocity to track the reference trajectory very closely and brings the ink channel to rest soon after jetting the ink drop as seen in the Fig.5 where we compare  $y_{opt}(t) = H(z)u(t, \theta_{opt})$  to the meniscus velocity corresponding to the standard pulse.

Given the behavior in the Fig.5, ink drops can be jetted with higher frequencies using the optimal actuation pulse. Fig. 6 shows the response of the ink channel when ten ink drop are jetted at DoD frequency 38kHz, i.e., the time interval between the initiation of two actuation pulses is  $(1/38)ms$ . In this figure, we compare the behavior when

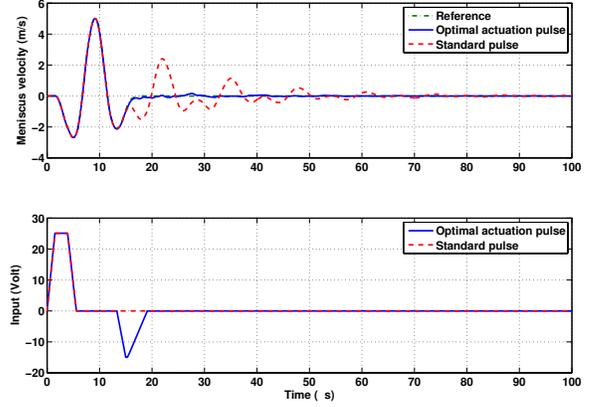


Fig. 5. Response of the meniscus velocity to the standard and the optimal actuation pulse.

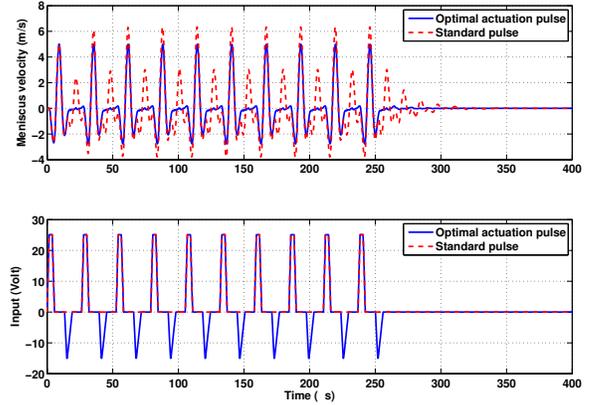


Fig. 6. Simulation for jetting of ten drops at DoD frequency 38kHz.

the standard and the optimal pulses are used. The meniscus velocity does not quickly come to rest after jetting the ink drop for the standard actuation pulse. Therefore, the initial conditions are different before application of the actuation pulse. This causes the velocity-peaks to change for subsequent drops indeed observed in the Fig.6, they are not equal to 5 as in the Fig.4. Recall that the velocity peak is a major feature and that a changed velocity-peak will result in drops having different velocities. These short-comings are not seen with the optimal piezo actuation pulse. It ensures similar initial conditions before the application of the resonating pulse for each ink drop. The difference in the velocity-peaks for the optimal actuation pulse are almost negligible. This will result into ink drops having almost the same velocity.

We have done similar experiments at different DoD frequencies to analyze the improvement in the performance of the inkjet printhead. However, we do not have enough space to provide all the results in this paper. Therefore to summarize all the results, we have only plotted the velocity-peak of the tenth drop against the DoD frequency in Fig.7.

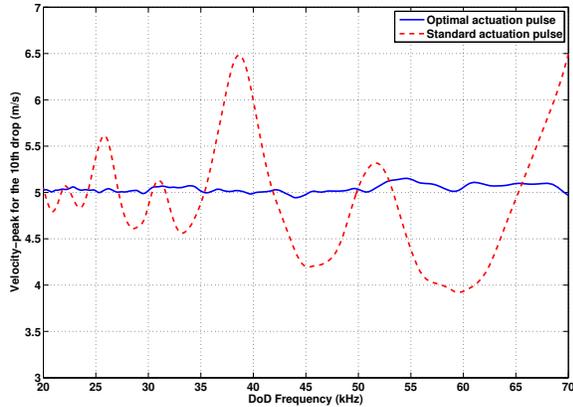


Fig. 7. Simulated DoD curve.

As the velocity-peak is almost equal to the velocity of the jetted drop, Fig.7. is equivalent to the ‘DoD-curve’, which is the benchmark defined in the introduction. We have seen previously that the standard pulse is not able to bring the ink channel to rest quickly. The time allowed for the residual oscillation to settle down will reduce as we increase the DoD frequency. Therefore, as shown in the Fig.7, the variation in the peak meniscus velocity becomes larger at higher DoD frequency when we consider the standard pulse. As opposed to this, the variation of the velocity-peak with the optimal pulse is very limited.

## V. EXPERIMENTAL RESULTS

The simulation results show that significant improvements can be achieved by using the optimal piezo actuation pulse  $u(t, \theta_{opt})$ . In this section we present experimental results to validate this claim. The experimental setup is equipped with a CCD camera which can capture the images of jetted drops at an interval of  $10\mu s$ . In each experiment we have jetted 10 ink drops from the inkjet channel at a fixed DoD frequency. All the images are placed adjacent to each other in the order of the time instant when they are taken. The composite image constructed in this manner for a DoD frequency equal to 46kHz is shown in Fig.8. This image shows the flight profile of the ten drops from the nozzle to the paper. The vertical axis represents the position of the ink drop. The starting position is the nozzle level and the paper is placed at the end position. The distance between the nozzle and the paper is approximately 2mm.

Ideally, it is required that the ten drops should be placed at an equal distance on the paper. In Figure 8, we compare the result with the standard pulse (Fig. 8a) with the optimal pulse (Fig. 8b). Fig.8a. shows that for the standard pulse, the first drop travels to the paper. However, the jetted drops subsequently has different velocities and they are slower than the first drop. Therefore, they get merged into a single drop before reaching the paper. Consequently, only two drops eventually reach the paper and they are placed far away from each other. For the optimal actuation pulse, all the jetted

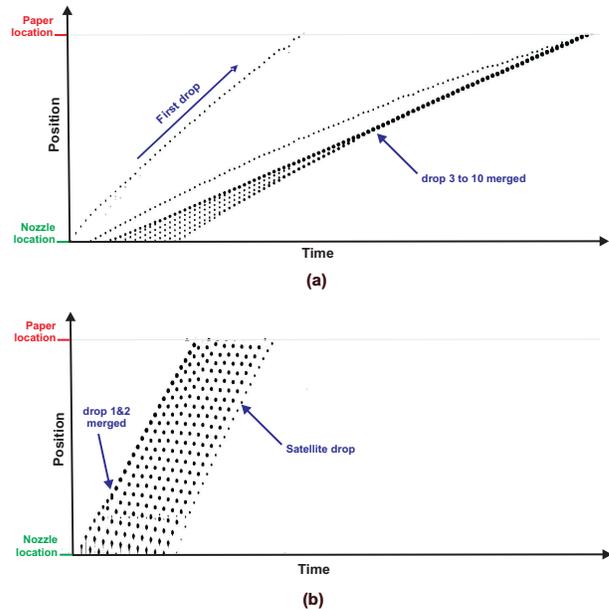


Fig. 8. Ten drops jetted at DoD frequency 46kHz, (a) standard pulse, (b) optimal actuation pulse.

drops have almost the same velocity (see Figure 8.b.). Since they have similar velocities, they drops are consequently placed at an equal distance on the paper. The first drop is slower and hence caught by the second drop. A small satellite drop is also visible after the tenth drop.

A number of experiments were carried out for different DOD frequencies ranging from 20kHz to 70kHz and interspersed at 2kHz. The drop velocities of each of the ten drops are shown in Fig.9 and 10 as a function of the DoD frequency (DoD curve). Fig.9 is obtained when the standard pulse is used and Figure 10 shows the results when the optimal pulse is used. We will evaluate the performance based on three aspects. First, we compare the velocity variation of the tenth drop over the DoD frequency range. The velocity of the tenth drop for the standard pulse varies from  $5.5ms^{-1}$  to  $14.5ms^{-1}$ . For the optimal actuation pulse this variation is considerably smaller, the velocity of the tenth drop varies from  $5.5ms^{-1}$  to  $9.8ms^{-1}$ . Second, at each DoD frequency we look at the velocities of the individual drops. It is very clear that at a fixed DoD frequency, the velocities of the ten drops are quite different for the standard pulse. On the other hand, individual drop velocities are very similar when the optimal pulse is applied to the inkjet printhead. Third, the behavior of the first drop is analyzed over the DoD frequency range. In Figure 9, we observe that, for the standard pulse, the first drop behaves very differently compared to the subsequent nine drops. When the first drop is faster than the subsequent drops, it will be placed far away from the subsequent drops (see Fig. 8a). This can affect the print quality severely. As the first drop is placed far apart from the rest of the drops, it indeed appears like a shadow of the printed bitmap to human eyes. When the optimal pulse is used, the difference between the first and the subsequent

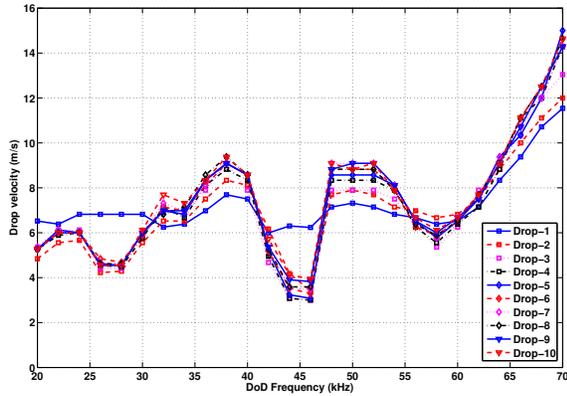


Fig. 9. Experimental DoD curve with the standard pulse.

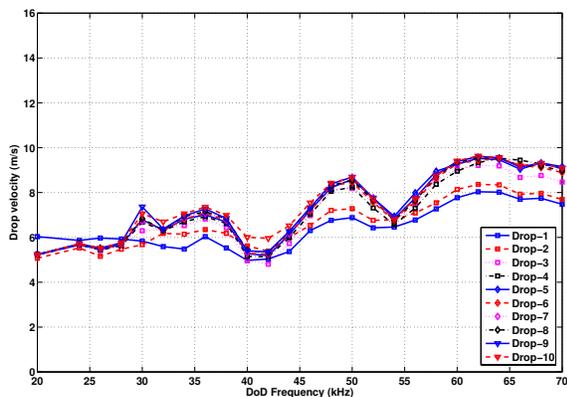


Fig. 10. Experimental DoD curve with the optimal actuation pulse.

drops is much less significant. Hence, a bitmap printed with the optimal pulse will not suffer from the shadow effect. The overall improvement in the velocity consistency achieved using the optimal piezo actuation pulse has a far reaching consequences for the print quality. This is because of the proximity of the inkjet printhead to the printing paper. Of course bringing back the residual oscillations to zero does not completely flatten the DoD curve this could be explained by modeling error.

## VI. CONCLUSIONS

In this paper we have proposed an optimization-based feedforward control law to damp the residual oscillations in a DoD inkjet printhead. The simulation results show that the proposed method can very effectively damp the residual oscillations enabling the ink channel to jet ink drops at higher jetting frequencies. Experimental results have demonstrated that considerable improvement in the ink drop consistency can be achieved with the proposed method. The difference between the experimental and the simulation results is attributed to modeling error.

Further improvements can be achieved through a more

accurate ink channel model or with an extension of the proposed method to handle the parametric uncertainties. This is subject of ongoing research. Applications of the proposed method to multi-channel control will be investigated in the future.

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